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USSR Report

MILITARY AFFAIRS

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USSR REPORT

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CYBERNETICS IN MILITARY SYSTEMS

Moscow KIBERNETIKA V SISTEMAKH VOYENNOGO NAZNACHENIYA in Russian 1979 signed to press 16 May 79 pp 5-36

/Chapter 1 by Viktor Nikolayevich Zakharov from the book "Kibernetika v Sistemakh Voyennogo Naznacheniya" eidted by him, Voyennoye Izdatel'stvo Ministerstva Oborony SSSR, 7,500 copies, 263 pages/

[Text] CHAPTER 1. GENERAL PRINCIPLES OF THE CONSTRUCTION OF CYBERNETIC SYSTEMS

1.1. Operating Principle of a Cybernetic System

A cybernetic system (Figure 1.1) consists of five component parts: the object of control (controlled process), the control system (control algorithm), the measuring system (sensors of the process's characteristics), the assigning system (program), and the monitoring system (monitoring algorithm). These parts are connected to each other and form two control circuits: the basic circuit with feedback through the measuring system (units 2, 1 and 3) and the auxiliary circuit (units 5, 4, 2 and 1).

The basic circuit insures the operation of the cybernetic system during the process of the development of signals R from the assigning system and has the purpose of maintaining the values of the object's output coordinates Y in accordance with those required by the assigning signals R in such a fashion that the error E = R - X is within given limits. Besides this, the basic circuit must be stable and have the required quality indicators for the system's transient process.

The auxiliary circuit insures the monitoring of the system's operation. In the case of any abnormalities in its operation, this circuit readjusts the assigning system's algorithm and changes the control system's algorithm for the purpose of insuring normal functioning of the basic circuit. The object of

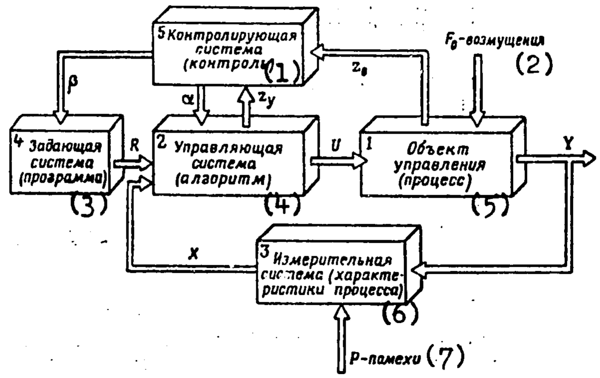

Figure 1.1. Functional diagram of a cybernetic system.
Key: 1. Monitoring system (monitor)
2. Disturbances
3. Assigning system (program)
4. Control system (control)
5. Object of control (process)
6. Measuring system (of the process's characteristics)
7. Interference

control can be any material body or any physical process, such as a rocket, a submarine, an airplane, the temperature and pressure inside a closed volume, the fuel combustion process in a reactor, and so on.

With the help of sensors, the measuring system measures the actual values of the object's or process's output parameters, which -- regardless of their physical meaning -- are called the generalized output coordinates Y.

In accordance with the control algorithms incorporated in it, the control system sends signals to the power members, which in turn provide the necessary effects U on the object. Thus, the control actions are worked out in accordance with the information produced by the sensors of the object's actual generalized output coordinates and their required values, as produced by the assigning system. This control principle is called deviation control and insures the high quality of a cybernetic system's operation. The set of devices consisting of the sensors and the assigning and control systems is called the regulator.

As the control system it is possible to use, for example, a digital computer or any combination of equipment and man. In accordance with the algorithms incorporated in it and the initial data, the assigning system works out the program for the change in the required values of R. The signals from the assigning device that enter the control system are called assigning actions.

The monitoring system serves to monitor the correctness of the system's functioning and to reorganize the algorithms for producing the control and assigning actions. If malfunctions and failures of individual elements appear, the monitoring system sends correcting signals (α, β) to the control and assigning systems in accordance with the actual state of the control parameters (Z_O, Z_Y). The system's hierarchical principle of construction provides it with increased reliability and vitality. It is important to mention here that the system operates with random, previously unknown external disturbances F_O acting on the object. In addition to this, there can be random interference P in the measuring system's sensors, so at the sensors' output we receive signals X, by which it is possible to determine the approximate values of the output coordinates Y of the state of the object.

1.2. Classification of Cybernetic Systems

Systems are classified according to three indicators: purpose, the form of the dynamic processes, and the degree of perfection.

All cybernetic systems are divided into two classes: automatic and automated systems (Figure 1.2).

The first class includes systems that function automatically, without the direct participation of a person (operator) during the generation of the control signals; an example of this is a flight control system for a rocket.

The second class consists of systems that operate with the direct participation of a person (or collective of people); examples of this class of system are an aircraft flight control system, a system for changing a ship's course, and so on.

Composite systems, in which the same system can be regarded as automatic in some functional modes and automated in others, are also encountered in practice. For example, in the absence of interference the tracking of a radar target proceeds automatically, while under complicated interference conditions it is tracked by a person (operator).

It should be kept in mind that the theory of automated systems has not yet been sufficiently fully developed, since it is still not possible to describe the behavior of man in the system adequately, with a degree of approximation to actual

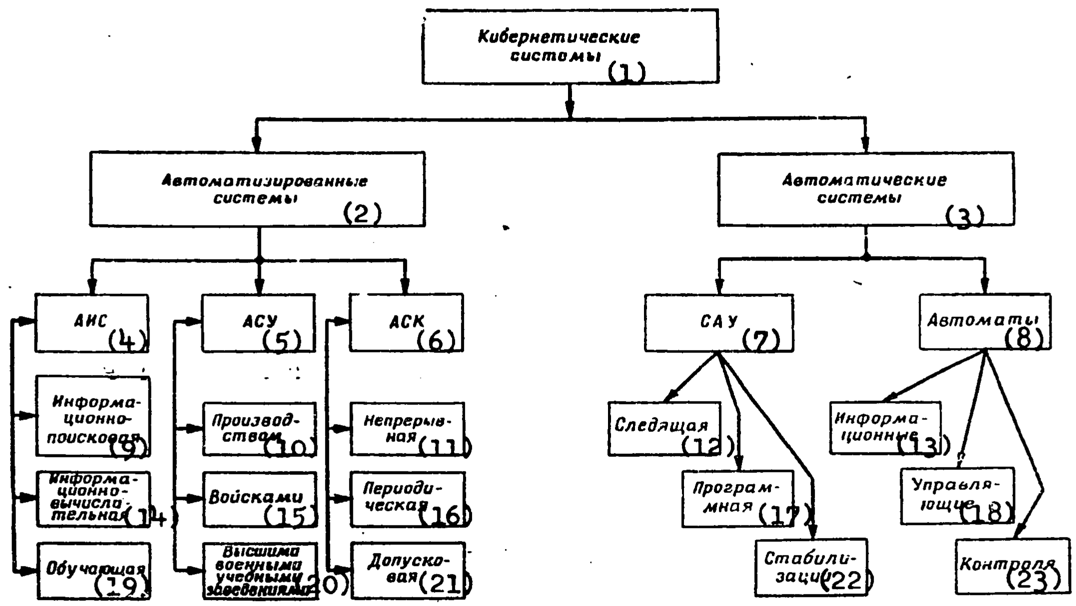

Figure 1.2. Classification of cybernetic systems.

Key:
1. Cybernetic systems
2. Automated systems
3. Automatic systems
4. AIS
5. ASU
6. ASK
7. SAU
8. Automata
9. Information retrieval
10. Production
11. Continuous
12. Servosystem
13. Information
14. Information and computing
15. Troops
16. Periodic
17. Programmed
18. Controlling
19. Teaching
20. Military VUZ's
21. Tolerance
22. Stabilization
23. Monitoring

reality that is sufficient for practical purposes, by means of mathematical relationships.

In turn, automatic and automated systems can be divided into a number of subsystems. In particular, automatic systems are subdivided into automata and automatic control systems (SAU).

Automata are divided into the following types, according to their purpose: information, control, and monitoring. Typical representatives of automata are robots and digital computers. The simplest automata include instruments for monitoring environmental parameters such as gas composition, temperature and so on.

A more complicated automaton is the perceptron, which is a device for recognizing patterns. This type of automaton includes, for example, reading machines. From the viewpoint of cybernetics, the basic feature of an automaton is the fact that its operation is determined by a finite number of states that replace each other according to a completely defined program.

According to the form of the assigning signals, automatic control systems are subdivided into programmed systems and servosystems. In servosystems the law governing the change in the assigning actions is unknown beforehand and the actions, as a rule, are of a random nature. An example of such a system is a radar station that tracks aircraft for the purpose of determining their flight parameters. In contrast to a servosystem, a programmed SAU operates according to an assigning action that is known beforehand. For example, the control system of a missile of the "ground-to-ground" type turns its axis through a pitch angle in accordance with the previously given program for turning during the active section of the flight trajectory.

Let us mention here that in some cases an SAU can contain some kind of automaton. An example of such a system is a control system for a rocket with an on-board digital computer. In this case the computer (automaton) acts as the control system.

Automated systems are divided into the following subsystems, according to purpose: automated information systems (AIS), automated control systems (ASU) and automated monitoring systems (ASK).

In turn, each of these subsystems is subdivided by purpose into separate types, as shown in Figure 1.2.

An automated information retrieval system (IPS) is used to collect, sort and store information and produce different references and information at the user's request. In foreign armies (such as that of the United States, which uses a TOS ASU), such systems serve the commanders and staffs of units (soyedineniye) and formations (ob"yedineniye), keep track of personnel, equipment and weapons, and store and produce information on the combat readiness of units (chast'), among other things.

In addition to collecting and processing information on the state of one's own troops and data on the enemy, information and computing systems (IVS) perform the calculations needed for the purpose of making recommendations and varying the conduct of combat activities. Besides this, these systems support the daily activities of troops for the purpose of maintaining them in a state of high combat readiness.

In accordance with a personnel training assignment formulated by the commander, an automated information system for teaching (ISO) carries out a sequential teaching process without the direct participation of a teacher. The simplest examples of such systems are different types of training equipment. More complicated ISO's contain digital computers with specially developed teaching programs.

Automated control systems are used to control processes and have different purposes. Such systems include, for example, control systems for complexes of weapons, troops, transportation and communication facilities, production process control systems, and so forth.

Finally, automated monitoring systems are classified according to their mode of operation: continuous action, periodic action and tolerance. Continuous- and periodic-action ASK's require no explanation. Tolerance ASK's provide for the transmission of an alarm signal whenever any parameter of the controlled process goes beyond a given limit.

The set of AIS, ASU, ASK, SAU and automaton subsystems insures integrated automation of weaponry control on a scale of the type encountered in the armed forces. Such a "system of systems" is called a "large system." The theory of "large systems" is being worked out and developed intensively at the present time and is intended for the solution of the problem of the efficient use of the systems involved.

Optimization of a cybernetic system is a central problem that is subject to solution during the creation of new complexes. The solution of this problem is based on two principles: Bellman's optimality principle and Pontryagin's maximum principle. The realization of these principles during the synthesis of specific SAU's is accomplished by the following methods:

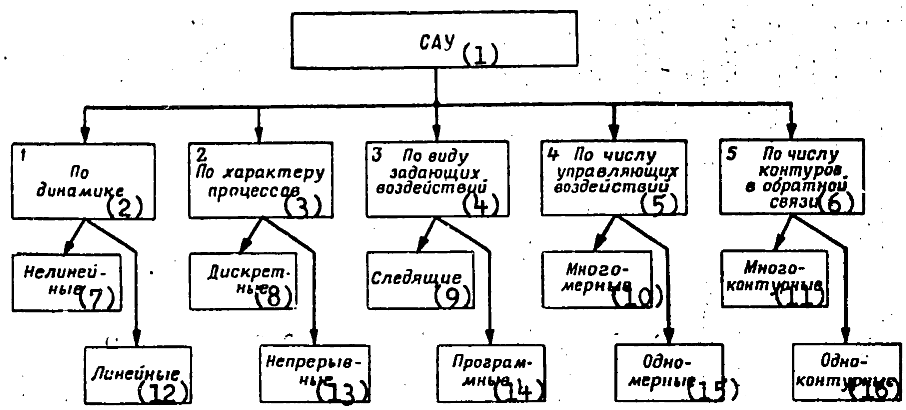

Figure 1.3. Classification of SAU's by dynamic and structural features.

Key:

1. SAU
2. By dynamics
3. By the nature of the processes
4. By the type of assigning actions
5. By the number of control actions
6. By the number of feedback circuits
7. Nonlinear
8. Discrete
9. Servo
10. Multidimensional
11. Multicircuit
12. Linear
13. Continuous
14. Programmed
15. Unidimensional
16. Single-circuit

frequency methods, dynamic programming, space of states, and others.

In order to use one method or another, it is necessary to present a clearcut classification of SAU's according to dynamic and structural features (Figure 1.3). This classification contains five characteristic features. The systems are divided into two mutually exclusive types for each feature.

According to the dynamic features, SAU's are subdivided into linear and nonlinear systems. It should be kept in mind that in view of the limitations that are imposed on control actions and the operating bands of sensors, all systems are nonlinear to some degree. However, if the deviations of the output coordinates during the process of SAU operation are within the given limits and the processes in the system are described by linear differential and nonlinear difference equations, the system can be considered to be linear.

SAU's are divided into continuous and discrete systems according to the nature of the processes taking place in them. In the first case the sensors measure the object's output coordinates continuously and the control system also generates the control actions on the object on a continuous basis. In the second case the system operates in an intermittent mode. The sensors measure the output coordinates periodically or the signals at the sensors' outlet are interrupted periodically, and the control signals at the control system's outlet are also of the intermittent type. Discrete systems include, for example, any SAU with a digital computer in the control circuit, since because of its operating principle a digital computer can receive and send out signals only at discrete points in time.

According to the nature of the assigning action that is generated, systems are subdivided into programmed systems and servosystems. This classification feature was discussed earlier.

On the basis of the number of independent control actions, SAU's are divided into uni- and multidimensional types. In the first case only one control signal can act on the object, whereas there can be several such signals in the second case.

According to the number of control circuits, systems are classified as single- or multicircuit. In the first case only one output coordinate is measured by a sensor and only a single feedback from the object to the control system is organized. In the second case the sensors measure several output coordinates and several feedbacks to the control system are organized. The number of circuits in the system is determined by the number of sensors. The circuits can be both internal and external. A multicircuit system with internal circuits frequently leads to a single-circuit structure with a single external circuit by way of shunting of the internal circuits.

From the viewpoint of analyzing and synthesizing SAU's, the upper row of the final classification in Figure 1.3 defines the more complicated system, while the lower row indicates the simpler SAU. In the first case the system is characterized as nonlinear, discrete, of the servo type, multidimensional and multicircuit, whereas in the second it is linear, continuous, programmed, unidimensional and single-circuit.

Although the classification presented above encompasses all types of SAU's, it still does not give a complete description of all their properties. In particular, using this classification it is difficult to give a full characterization of a system's degree of perf ction. Therefore, let us discuss a supplementary classification according to this feature (Figure 1.4).

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Figure 1.4. Classification of SAU's according to degree of organization and perfection.

Key:

1. Self-organizing
2. Self-learning
3. Adaptive
4. Extreme
5. Self-adjusting
6. Closed-loop
7. Open-loop

As far as the degree of perfection is concerned, the simplest systems are open-loop SAU's, although they -- as has already been mentioned -- are frequently unable to function. Closed-loop systems (or systems with feedback) are an improvement. In them the control actions are generated according to deviations of the actual output coordinates from the required values. The operating principle of a closed-loop SAU was discussed in detail in Section 1.1.

The next higher level of organization belongs to self-adjusting SAU's, in which the control algorithm's parameters are reorganized without reorganizing the structure of the algorithm itself. The reorganization of the parameters takes place as the SAU operates in accordance with the change in the previously selected indicators for the quality of the work. The functional diagram of a self-adjusting SAU contains a monitoring system, while the block diagram is supplemented with a self-adjustment circuit.

In a self-adjusting SAU, if there is a search for the extreme value of the quality indicator and the processes are kept close to this extreme level under conditions where the system is acted on by external disturbances and interference, this system is called an extreme one.

Even more improved and more complexly organized is a self-adjusting SAU in which not only the control algorithm's parameters, but also its structure is reorganized. Such a system is adaptable to changing conditions in the external medium and is called adaptive.

At the sixth level of perfection and organization we find self-learning SAU's in which, in accordance with a selected learning strategy, optimal control algorithms are worked out according to given quality indicators. Of course, before such a system can operate effectively, it must spend some time on the development of the control algorithm; that is, on self-learning. At the same time, when there is an unforeseen change in the external operating conditions or the object's internal structure, the system "learns" anew, thus adapting to these changes. Let us mention here that the theory of such SAU's is not fully developed at the present time and that the systems themselves are far from being realized in practice.

The highest degree of perfection and organization is possessed by self-organizing SAU's, which not only generate the optimum algorithm during the process of operation, but also select the learning strategy according to the target function incorporated in it. However, technical systems of this type have apparently not yet been developed and will not be in the foreseeable future.

1.3. Examples of Cybernetic Systems

1.3.1. Flight Control System of an Intercontinental Ballistic Missile

As an example of a discrete, multicircuit SAU for military purposes, let us discuss the flight control system of a "Minuteman" missile [2]. As is known, the Minuteman is a three-stage intercontinental ballistic missile (MBR) with solid-fuel engines that has an inertial guidance system and an on-board digital computer (BTsVM) in the control circuit for the movement of the center of mass and stabilization relative to the center of mass.

Figure 1.5 depicts the design and functional diagram of this missile's flight control system. The inertial navigation unit consists of a gyrostabilized platform with pitch ($\Delta\Theta$), yaw ($\Delta\psi$) and rotation ($\Delta\varphi$) angle sensors. On the gyrostabilized platform there are three linear accelerometers that measure accelerations in three mutually perpendicular directions (x,y,z). On the basis of the signals from the accelerometers, a calculating and problem-solving unit determines the increments in the linear velocities ($\Delta V_x,\Delta V_y,\Delta V_z$) of the missile's center of mass in inertial space. In the second stage of the missile there is an additional angular accelerometer that measures deviations of the missile hull's angular velocities of rotation relative to the pitch ($\Delta\dot{\Theta}_a$) and yaw ($\Delta\dot{\psi}_a$) angles.

Signals from the accelerometers enter the VTsVM, which works out the output control signals for the purpose of stabilizing the missile's axes relative to the pitch, yaw and rotation angles and for controlling the center of mass's movement in the directions that are lateral and normal to the flight trajectory.

Thus, this system is a multicircuit and multidimensional discrete SAU. The system's distinctive feature is the use of a

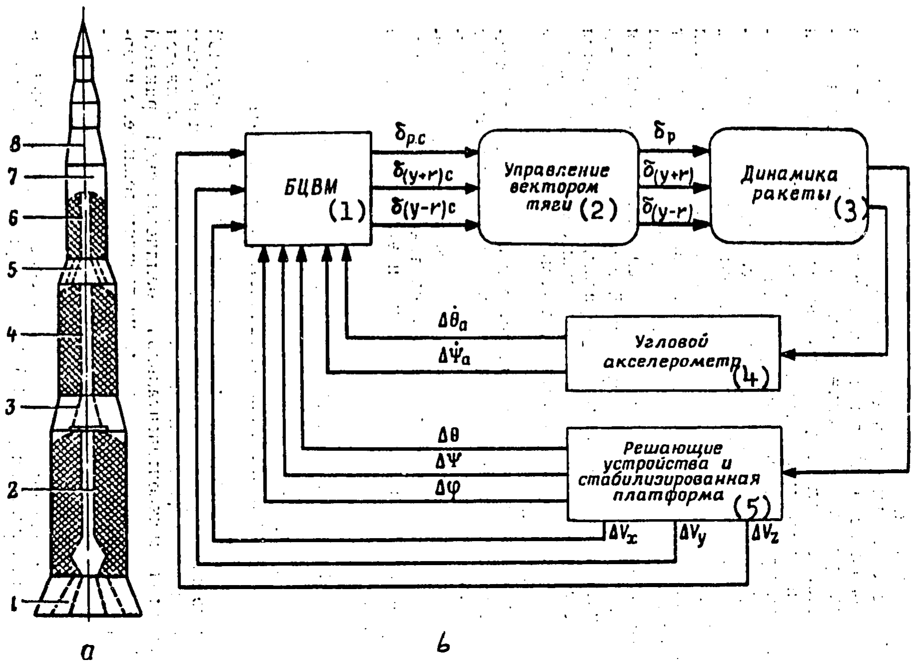


Figure 1.5. Minuteman intercontinental ballistic missile: a. missile; b. functional diagram of flight control system; 1. four rotating nozzles with angle of deflection sensors; 2. first stage; 3. transitional compartment between first and second stages; 4. second stage; 5. transitional compartment between second and third stages; 6. third stage; 7. instrument compartment (three accelerometers); 8. control and navigation systems' equipment compartment.

Key:

1. VTsVM
2. Thrust vector control
3. Missile dynamics
4. Angular accelerometer
5. Problem-solving units and stabilized platform

VTsVM with additional devices for converting analog (continuous) signals into discrete (digital) ones and vice versa. The VTsVM has a high operating speed and a memory that is adequate for controlling the missile with given quality indicators. The $\Delta\Theta$, $\Delta\psi$ and $\Delta\varphi$ output signals are quantified with respect to time, with a discreteness period $T_{01} = 0.03$ s, while the ΔV_x, ΔV_y and ΔV_z signals have a discreteness period $T_{02} = 0.45$ s. The output control signals enter the drive mechanisms with a period $T_{01} = 0.03$ s.

The use of the VTsVM provides the missile's control system with flexibility because the parameters of the algorithms for generating the stabilization and guidance signals, which are stored in the computer's memory, can be changed quite easily. For example, the missile can be retargeted and the flight assignment changed by entering new constants in the VTsVM's memory unit.

Thus, the integrated system for controlling the state and launching of the missile is automated and functions with the participation of an operator. After the launch command is transmitted, the system functions automatically.

1.3.2. Orientation and Stabilization System of an Orbital Space Station

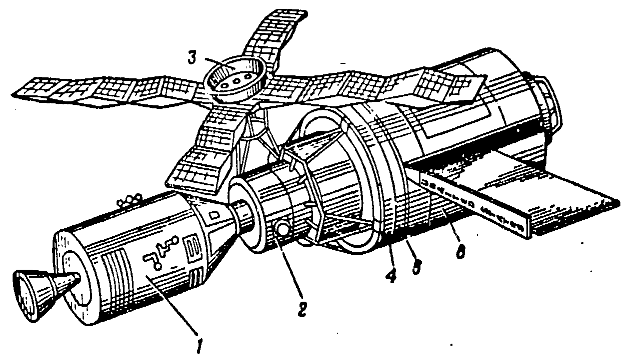


Figure 1.6. General view of the "Skylab" orbital station: 1. "Apollo" spacecraft; 2. docking unit (two docking assemblies); 3. astronomical instrument complex; 4. lock chamber; 5. instrument compartment; 6. basic station unit.

Let us discuss the purpose and operating principle of the orientation and stabilization system for the Skylab semipermanent, inhabited space station [9]. This station is not a military project, but from the viewpoint of the construction of the cybernetic system it can be regarded as an example of a modern SAU with a BTsVM in the control circuit. Figure 1.6 is a general view of the station with a docked Apollo spacecraft. In order to support the conduct of experiments requiring accuracy of orientation and stabilization on the order of several angular minutes, a special astronomical compartment (3) located in a separate structure is used. This compartment can rotate relative to the basic unit (6) of the orbital station.

Increased accuracy in the stabilization of the astronomical compartment is provided by vernier control of the compartment's

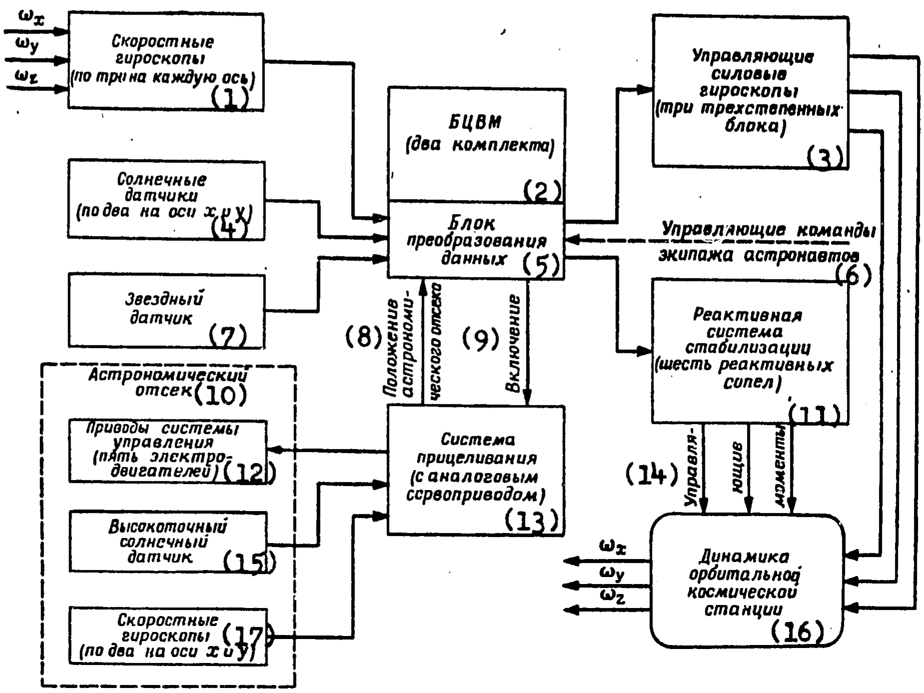


Figure 1.7. Functional diagram of orbital space station's orientation and stabilization system.

Key:

1. Rate gyroscopes (three on each axis)
2. VTsVM (two complexes)
3. Powered control gyroscopes (three three-stage units)
4. Solar sensors (two each on x and y axes)
5. Data conversion unit
6. Astronaut crew control commands
7. Stellar sensor
8. Position of astronomical compartment
9. Engage
10. Astronomical compartment
11. Jet-powered stabilization system (six jet nozzles)
12. Control system drive mechanisms (five electric motors)
13. Aiming system (with analog servomotor)
14. Control moments
15. High-precision solar sensor
16. Orbital space station dynamics
17. Rate gyroscopes (two each on x and y axes)

position with the help of a special servomotor. The stabilization system's sensors serve three rate gyroscopes that measure the station's angular velocities relative to the ω_x, ω_y and ω_z axes.

Powered control gyroscopes and jet nozzles are used to maintain the required orientation of the station's axes. The basic stabilization equipment consists of three-stage powered gyroscopes, the rotors of which spin at a speed of 9,000 r/min. The functional diagram of the orientation and stabilization system is shown in Figure 1.7.

The VTsVM uses the angular velocity sensors' readings to determine the station's position relative to the inertial space's fixed axes and generate the control signals to control the velocity vector. However, as the result of the accumulation of errors in the computation of the angles, such a system cannot insure the preservation of the required angular position of the station's axes for an extended period of time. Therefore, solar sensors and star trackers are used to supplement the system. The special feature of this system is its use of a centralized BTsVM that solves all the basic station control problems.

The BTsVM has the following specifications: time for a single cycle -- 3 μs; memory -- 16,000 sixteen-bit words; temperature range for normal operation -- from -40 to +75°C; data presentation -- with fixed decimal and parallel processing of individual bytes of information.

In order to insure its operational reliability, the BTsVM is duplicated: in the case of failure of the basic complex, a coupling unit provides for automatic switching of all circuits to the reserve complex. The BTsVM's memory has already had entered in it the programs for computing the orientation and stabilization control signals that are sent to the powered gyroscopes and, when necessary, to the jet nozzles' drive mechanisms. The command signals first pass through a digital filter in order to eliminate the undesirable effect of tones from elastic vibrations of the station's hull on the dynamics of the stabilization system. The discreteness period during the transmission of the control signals to the powered gyroscopes is 0.2 s.

Thus, this system is a multicircuit, multidimensional, discrete SAU with a variable structure and a single BTsVM in the control circuit.

1.3.3. Automatic Flight and Weapons Control System for a Strategic Bomber

Let us discuss the realization and operation of an integrated system, using the control system of the United States' multipurpose FB-111 aircraft as an example [5]. This aircraft's complex of on-board data equipment (Mk. 2) is intended to

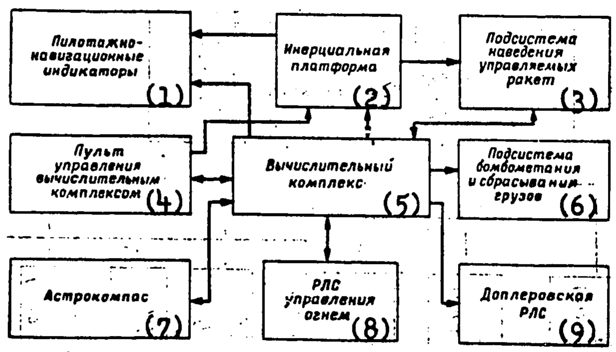


Figure 1.8. Functional diagram of the on-board equipment complex of the FB-111A airplane.

Key:

1. Pilot's navigation display
2. Inertial platform
3. Guided missile guidance subsystem
4. Computer complex control center
5. Computer complex
6. Bombing and cargo-dropping subsystem
7. Astrocompass
8. Fire-control radar
9. Doppler radar

provide semiautomatic and automatic aircraft flight modes and to control the launching and guidance of guided missiles of the air-to-ground type.

The bomber can carry six SRAM missiles [22]. They are launched at a distance of 60-160 km from the target, after which the airplane turns to the opposite heading.

Figure 1.8 is the functional diagram of the FB-111A aircraft's complex of on-board equipment. On the airplane there are also terrain-following radar, a radio altimeter, a unit for detecting enemy radar in operation, electronic countermeasures devices and other auxiliary equipment. The distinctive feature of this complex is the presence of two BTsVM's of the 4Pi (AN/AYK-6) type and a conversion unit that links the BTsVM's to the sensors and the other on-board equipment. One of the BTsVM's is used to make navigation calculations and, in particular, to insure the generation of signals to correcto the position of the inertial platform during flight, while the other generates weapons control commands and signals.

The BTsVM is based on integrated circuits. In order to insure the operational reliability of the digitual computation complex in case of failure of one of the BTsVM's, an auxiliary operating mode with switching in of the second computer is provided. If one of the BTsVM's fails, the conversion unit and the couplings insure that the signals from the sensors are switched to the one that is in good working order.

Specifications of 4Pi BTsVM

Weight	21.3 kg
Volume	22 dm^3
Required power	240 W
Word length.	16-32 binary digits
Capacity of main memory.	8,448-33,792 words
Operation execution time:	
Addition	5 μs
Multiplication	19.4 μs
Division	46.3 μs

The SRAM supersonic guided missile (Figure 1.9) is used to arm existing and prospective strategic bombers (FB-111A, B-52G/H, B-1) and has the purpose of suppressing radar and antiaircraft weapons when breaking through an enemy's air defenses, as well as that of destroying the main target. The missile can carry a nuclear warhead. Flight control is exercised by an inertial guidance system consisting of an autopilot, a computer and a radar altimeter.

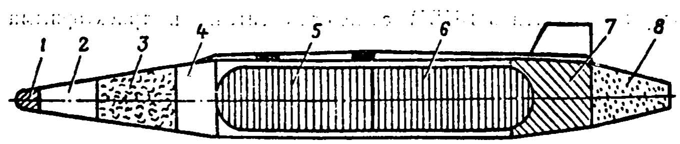


Figure 1.9. Layout of SRAM missile: 1. impact detonator; 2. compartment for guidance system; 3. nuclear warhead; 4. guidance and control system compartment; 5. solid-fuel propellant; 6. solid-fuel launching charge; 7. tail section with actuating equipment of control system; 8. tail cone.

The method for guiding the missile to the target, which provides a flexible flight trajectory with maneuvering in the vertical and horizontal planes, is called "guidance to an imaginary target." The spatiotemporal coordinates of the imaginary target in the missile's guidance section are generated in the on-board computer and changed in accordance with the previously chosen trajectory that passes through the actual target. The principle of guidance according to the imaginary target's trajectory is explained in Figure 1.10.

Beginning with the moment of its launch from the airplane, the missile is guided to the actual target by the method of pursuit

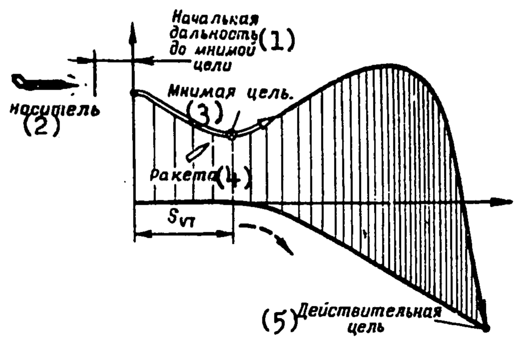


Figure 1.10. Missile guidance trajectory according to the method of pursuit of an imaginary target.

Key:

1. Initial range to imaginary target
2. Carrier
3. Imaginary target
4. Missile
5. Actual target

of the imaginary target. The imaginary target's trajectory is determined by 36 aiming constants that are stored in the carrier aircraft's BTsVM, as well as the trajectory algorithms that are incorporated in the missile's on-board computer. The missile's inertial platform is set up before it is launched. as the carrier aircraft is in flight, by singals from the airplane's reference bloc of inertial measuring units. The Kalman filter method is used to insure accurate orientation of the platform according to a 10-dimensional vector of state. Figure 1.11 depicts the functional diagram of the missile's flight guidance and control system.

On the basis of sensor signals and in accordance with the guidance algorithms, from the moment of the missile's launch its on-board computer determines the three orthogonal components of the mismatch between the position of the missile's center of mass and the point representing the imaginary target's location in the navigational system of coordinates ($\Delta x, \Delta y, \Delta z$). These values are filtered and converted into direct-current analog signals in accordance with the directing cosines. The analog signals are distributed among the channels of the connected system of coordinates with the help of angular sine-cosine converters that are oriented on the axes of the inertial platform's suspension system. As a result, signals are generated that are proportional to the angular errors Θ_ε, ψ_ε and φ_ε in the missile's orientation. These signals enter the autopilot's input as programmed signals; the autopilot then provides the necessary orientation of the missile's axes and guides its center of mass along the imaginary target's trajectory. It should

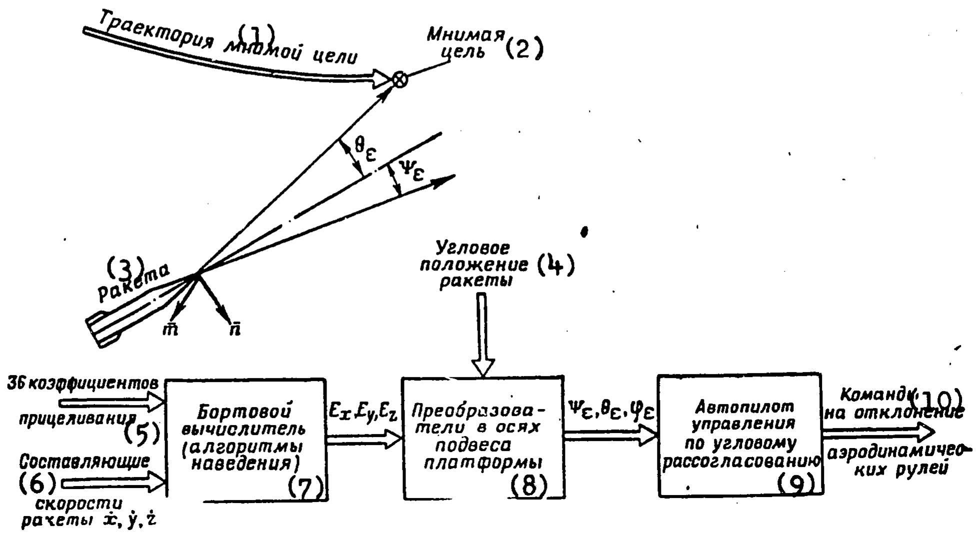


Figure 1.11. Functional diagram of missile flight navigation and control system.

Key:
1. Imaginary target's trajectory
2. Imaginary target
3. Missile
4. Missile's angular position
5. 36 aiming factors
6. Missile's velocity components $\dot{x}, \dot{y}, \dot{z}$
7. On-board computer (guidance algorithms)
8. Converters in platform suspension system's axes
9. Autopilot control by angular mismatch
10. Commands for deflection of aerodynamic rudders

be mentioned that the algorithms incorporated in the missile's on-board computer are quite simple, since the most complicated calculations to insure the orientation of the missile's inertial platform and determine the guidance parameters are done by the carrier aircraft's BTsVM.

Specifications of the SRAM Missile's On-Board Computer

Weight	2.3 kg
Volume	2.26 dm^3
Required power	45.5 W
Number of commands	11
Memory capacity.	2,048 8-bit binary words
Length of information word	18 binary bits
Addition operation execution time.	24 μs
Digital configuration of analog-to-code and code-to-analog converters.	9

Thus, the integrated flight control system of the FB-111A carrier aircraft with a SRAM guided missile is a compex, multicircuit and multidimensional discrete SAU with digital computers on board both the airplane and the missile.

1.3.4. Automated Weapons Control System for a Ship

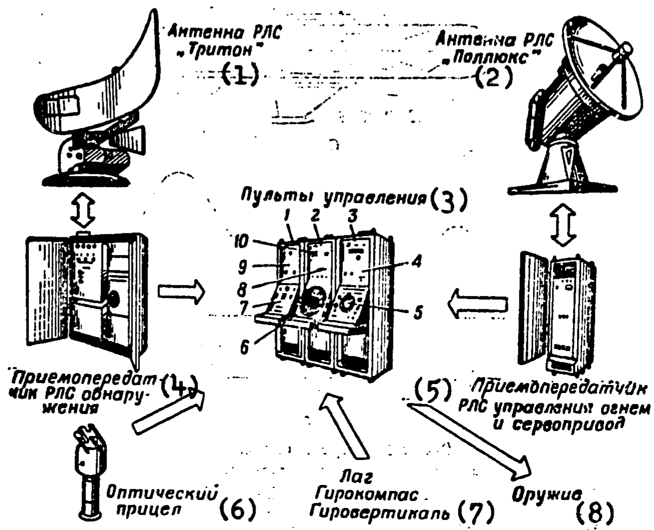
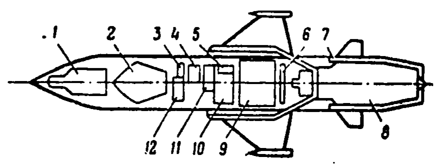


Figure 1.12. The "Vega" system: 1. missile and torpedo control panel; 2. target detection and acquisition panel; 3. artillery fire-control panel; 4. artillery unit control computer; 5. target tracking screen; 6. tactical situation screen; 7. weapon control panel; 8. unit for input of target movement and attacking ship's parameters into computer; 9. guided missile and torpedo fire-control computer; 10. automatic target-tracking unit.

Key:
1. "Triton" radar antenna
2. "Pollux" radar antenna
3. Control panels
4. Acquisition radar transceiver
5. Fire-control radar transceiver and servomotor
6. Optical sight
7. Log; gyrocompass; vertical gyroscope
8. Weapons

As an example of a modern ASU intended for the control of a ship's weapons, let us discuss the Vega system [12]. Eleven variants of this system are known, each of which is intended to control a certain, specific complex of weapons on board a ship. Figure 1.12 is a diagram of the Vega system. Each of the system's variants contains: a Triton radar for target acquisition and tracking and navigation; a Pollux or "Castor" radar for controlling the ship's weapons; a control panel combined with a TsVM [digital computer].

The shipborne TsVM in the Vega system processes the data needed to "capture" targets for the weapon-control radar, track them, and control the different weapon systems. For example, in the "Vega-Pollux-PCOT" system the TsVM generates the necessary data for controlling the fire of a ship's conventional artillery, launching "Ekzoset" [translation unknown] or "Automat" missiles, and firing guided torpedoes. The TsVM has a single central processor that operates in the multiprogram mode. The TsVM's operating is sufficiently fast (addition, multiplication and division of two 16-bit binary words require 2, 5 and 4 s, respectively) so as to enable it to operate in the control circuits in real time.



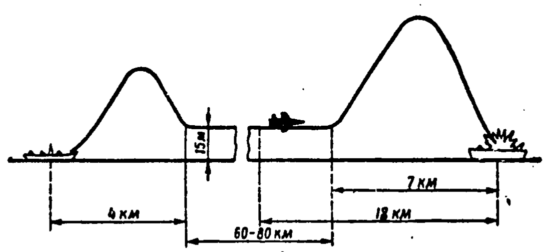


Figure 1.13. The Automat missile: a. layout; b. flight trajectory; 1. active radar homing head; 2. semi-armor-piercing warhead; 3. regulator; 4. control system bloc; 5. converter; 6. oil tank; 7. aerodynamic rudder servomotor; 8. turbojet cruise engine; 9. fuel tank; 10. computer and radar altimeter; 11. electronic equipment bloc; 12. inertial system bloc.

Let us discuss an automatic antiship missile control system, using an Automat missile [21] as an example. The missile's basic purpose is to destroy mobile surface targets at quite long ranges. The Automat missile's layout is shown in Figure 1.13a. The missile has five compartments: nose cone, warhead, instrument compartment, fuel tank and engine. The missile flies on a calculated trajectory. During the final section of its flight a radar homing system is engaged. The control system consists of an inertial unit, a radar altimeter, a computer, an active radar homing head, electronic equipment, and servomotors for the aerodynamic rudders.

The missile is launched from a container that is mounted stationarily on board a ship. The target is "captured" with the help of the ship's acquisition and tracking radar. Data on the target's parameters are sent from the radar to a TsVM, which simultaneously receives data on the carrier ship's speed, course and list and the wind parameters. In accordance with the algorithm previously incorporated in it, the TsVM works out the parameters of the missile's maneuver trajectory and calculates when the homing head should be turned on. These data are sent to the on-board computer in the missile's guidance system. A possible missile flight trajectory is shown in Figure 1.13b.

A standardized missile of the Automat type can be fired not only from ships, but also from airplanes, helicopters and even from coastal launching units. Analyzing the composition and purpose of the Vega system, we can conclude that modern automated and automatic control systems for shipborne weapons are multicircuit and multidimensional cybernetic systems with TsVM's on the ship and computing systems in the guided missiles.

1.3.5. Antiaircraft Missile Complex Control System

Let us discuss the purpose, composition and operating principle of an automated control system for an antiaircraft missile complex (ZRK), using the SAM-D system [13] as an example. The missiles in this complex are intended to destroy airplanes of the FB-111 type at different altitudes, air-to-ground rockets of the SRAM type, and tactical ground-to-ground missiles of the Lens type.

The complex consists of a control point, a multifunction radar with a phased antenna array (FAR), and launchers (Figure 1.14). The control point receives and processes all the initial information needed to operate the SAM-D system. Its equipment consists of a TsVM, a display unit, and a data transmission system.

The TsVM's operating speed is about 1 million operations per second and its memory has a capacity of 750,000 binary digits.

The XMIM-104 missiles in the SAM-D complex are guided by a combined method: in the initial stage of the flight they are controlled by commands from the radar, and in the final stage by semiactive guidance. In the final stage, the guidance commands are determined with the help of the radar's TsVM and then transmitted to the missile.

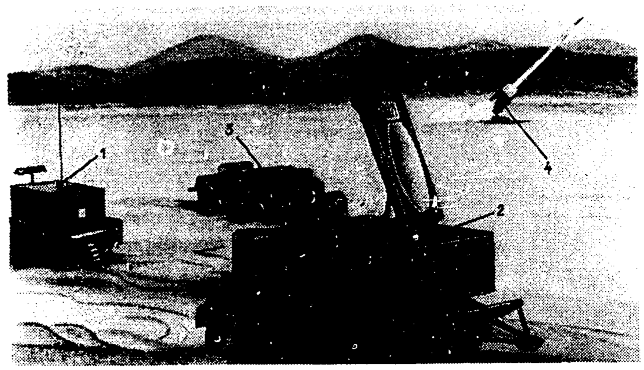


Figure 1.14. Placement of elements of SAM-D ZRK at the firing site (sketch): 1. control point; 2 multifunction radar with FAR; 3. military vehicle with launching containers; 4. launcher.

Thus, the ZRK automated fire control system is a complex multi-circuit and multidimensional system with a digital computer that provides for both the operation of the radar with the FAR and the generation of commands for guiding the missiles to the target.

1.4. Models of Automatic Control Systems

1.4.1. Continuous, Unidimensional Systems

Let us discuss the techniques for formulating the structural diagram of an SAU according to its functional diagram, using a system for pitch angle stabilization of a rocket as an example. Figure 1.15 is a functional diagram of such a system. When the system is in operation, a pitch-angle sensor mounted on a gyro-stabilized platform measures the deviation of this angle's actual value from the required value and converts the given deviation into a proportional voltage u_d, the polarity of which corresponds to the sign of the angle's deviation $\Delta\vartheta$. In order to insure the stability and quality of the entire stabilization system, voltage u_d is fed into an equalizer that is a component part of the amplifier-converter. From the equalizer's outlet, voltage u_k is fed into the amplifier, which -- in turn -- generates the control signals in the form of currents i_{II}, i_{IV}. These currents enter the control windings of steering actuators II and IV. The latter set the control elements in action by turning the rudder chambers through angles δ_{II} and δ_{IV}.

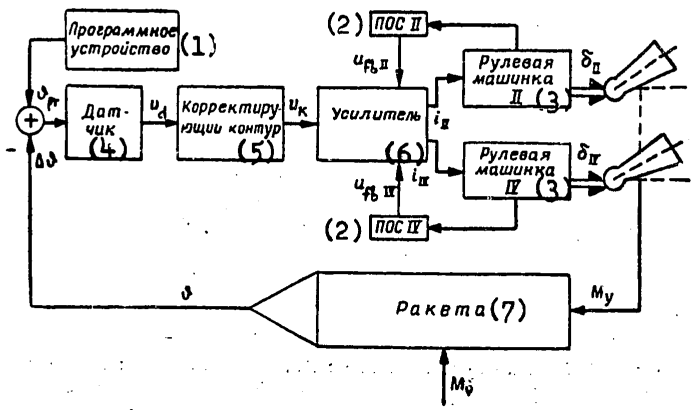


Figure 1.15. Functional diagram of a rocket's pitch angle stabilization system.

Key:

1. Programming unit
2. POS
3. Steering actuator
4. Sensor
5. Equalizer
6. Amplifier
7. Rocket

Thus, there appears a control action in the form of pitch control moment M_y. This moment insures the turning of the rocket with respect to the pitch angle so as to obtain the small deviation $\Delta\vartheta = \vartheta_{pr} - \vartheta$. The adduced signals and the actions form the basic closed-loop feedback circuit. However, it is not hard to see that in the system there also exist additional internal circuits from feedback potentiometers POS_{II} and POS_{IV}, which are mounted on the steering actuators' shafts. These additional negative feedback circuits insure the generation of the control voltage u_y. It can be assumed that the amplifier, the steering actuators and the feedback potentiometers form a servodrive. Therefore, after the inner circuit is rolled up and replaced with the servodrive, we reduce the two-circuit system to a single-circuit one.

Let us mention here that a previously unknown external disturbing moment acts on a rocket in flight. Besides this, the steering actuators have some creep; that is, a slow drift of their shafts from the zero position when there is a zero input signal i_y. It can be assumed that this drift appears because of an additional disturbance signal i_v.

The programming unit assigns the programmed value ϑ_{pr} of the pitch angle. In order to formulate the system's structural diagram, let us write the equations that describe the operation of the individual units and define the relationships between each unit's input and output signals:

$$\left.\begin{array}{l}
1.\ u_d = k_d(\vartheta_{pr} - \vartheta) = k_d \Delta\vartheta; \\
2.\ a_2 \dfrac{d^2 u_\kappa}{dt^2} + a_1 \dfrac{du_\kappa}{dt} + u_\kappa = b_0\left(T_1^2 \dfrac{d^2 u_d}{dt^2} + 2T_1\xi_1 \dfrac{du_d}{dt} + u_d\right); \\
3.\ i_y = k_y(u_\kappa - u_{fb}) = k_y \Delta u; \\
4.\ \dfrac{d\delta}{dt} = k_\delta (i_y + i_v); \\
5.\ u_{fb} = k_{fb}\delta; \\
6.\ \dfrac{d^2\vartheta}{dt^2} + c\dfrac{d\vartheta}{dt} + d\vartheta = e\delta + m_v.
\end{array}\right\} \quad (1.1)$$

In this system we have: 1 -- the sensor's equation; 2 -- the equalizer's equation; 3 -- the amplifier's equation; 4 -- the steering actuators' equation; 5 -- the feedback potentiometers' equation; 6 -- the pitch angle moment's equation. The coefficients of the following units have been defined in terms of k_d, k_y, k_δ and k_{fb}: the sensor, the amplifier, the sterring actuator and the feedback potentiometer. Coefficients a_2, a_1, b_0, T_1 and ξ_1 characterize the equalizer's properties. Coefficients c, d and e characterize the object's (rocket's) properties.

This system of equations can be regarded as a mathematical model of the stabilization system. In order to obtain a structural diagram, we should perform a Laplace transform operation on the left and right sides of all the equations that are part of the system for zero initial conditions. Allowing for the fact that in general form the representation of the derivative $(d^n x/dt) \div p^n X(p)$, where p = the Laplace variable and X(p) = the representation, we obtain

$$\left.\begin{array}{l}
1.\ u_d(p) = k_d \Delta\vartheta(p); \\
2.\ u_\kappa(p) = \dfrac{b_0(T_1^2 p^2 + 2T_1\xi_1 p + 1)}{a_2 p^2 + a_1 p + a_0} u_d(p); \\
3.\ i_y(p) = k_y \Delta u(p); \\
4.\ \delta(p) = \dfrac{k_\delta[i_y(p) + i_v(p)]}{p}; \\
5.\ u_{fb}(p) = k_{fb}\delta(p); \\
6.\ \vartheta(p) = \dfrac{e\delta(p) + m_v(p)}{p^2 + cp + d}.
\end{array}\right\} \quad (1.2)$$

On the basis of system of equations (1.2) it is not difficult to construct a structural diagram (Figure 1.16), where the operator transfer functions (OPF) of the system's separate components are located inside the rectangles. Where all the OPF parameters are known, this structural diagram serves as a basis for analyzing the processes in the SAU. However, if any of the OPF parameters of the components of the regulator are unknown

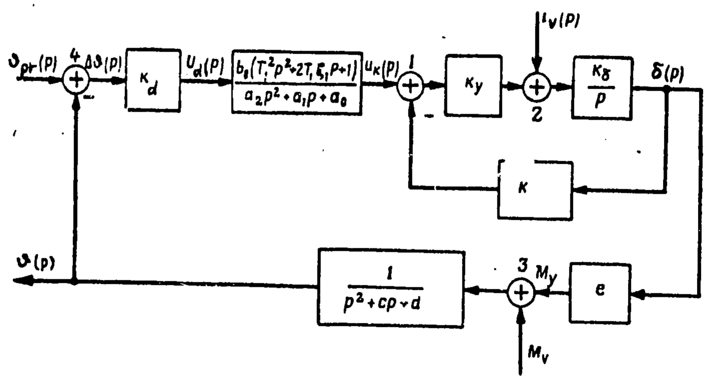


Figure 1.16. Structural diagram of a pitch angle stabilization system for a rocket.

beforehand, it is possible to formulate and solve the problem of synthesizing the SAU for a given form of the structural diagram; that is, the problem of selecting the regulator's parameters according to the given requirements for the system (as far as accuracy, operating speed and other quality indicators are concerned). If the form of the equalizer's OPF is not given, the more general problem of synthesizing the system according to a given quality indicator can be formulated and solved; that is, the problem of determining not only the parameters of the regulator's structure, but also the form of the OPF of the structure itself. In accordance with the classification given in Section 1.2, such a system can be regarded as linear, continuous, programmed, unidimensional, and double-circuited. In the case of convolution of the inner circuit, such a system is reduced to a single-circuit one.

1.4.2. Single-Circuit and Unidimensional Discrete Systems

Let us discuss a discrete, single-circuit object stabilization system, the distinctive feature of which is the presence of a TsVM in the control circuit. The use of a TsVM makes it possible to unitize and standardize the control equipment and provide self-monitoring both before and during operation. These properties are particularly important for military systems, where it is necessary to insure a high degree of combat readiness, accuracy and reliability.

Figure 1.17 is a functional diagram of a discrete SAU. In the diagram there are two switches that are closed in a short time interval with discreteness period T_0. The sensors are connected to the digital control unit (TsUM) by signal converters of the voltage-to-code type (N/K), while the TsUM is connected to

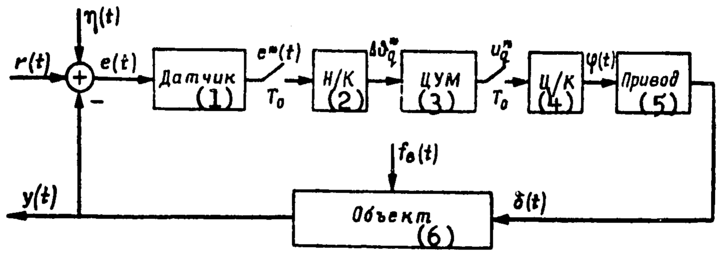


Figure 1.17. Functional diagram of a discrete, single-circuit stabilization system.

Key:

1. Sensor
2. N/K
3. TsUM
4. Ts/K
5. Drive
6. Object

the drives by a reverse converter of the digit-to-code type (Ts/K). The control signal that actuates the drive is read at this converter's outlet. For discrete systems, signals marked with the symbol * are discrete in time sequence. Figure 1.18

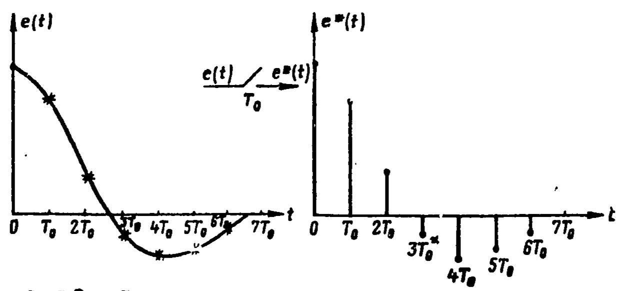


Figure 1.18. Conversion of continuous signal into a discrete sequence.

shows the principle of the conversion of a continuous, changing signal e(t) into a discrete sequence e*(t). It should be mentioned here that in connection with such a conversion, information on the input signal inside period T_0 is lost. It should also be kept in mind that the TsUM's and converters' input registers have a finite number of binary digits, so in addition to quantization of the input signal with respect to time, there is also signal quantization by level. In many cases, however, this conversion error is small and can be ignored in practical calculations. Therefore, we will henceforth limit ourselves to a discussion of only SAU's with time quantization of the signals. In the literature, such SAU's are frequently called pulse SAU's.

When analyzing and synthesizing SAU's with TsUM's, there is no need to discuss the layout of the regulator's equipment in detail. It is sufficient to determine the equations that connect the TsUM's output temporal sequences with the input sequences. Since the TsUM has memory cells, it can remember the values of the input and output signals during preceding moments relative to a given moment. In accordance with the previously selected algorithm, the TsUM can calculate the control signal's values according to the relationship

$$\begin{gathered} u[kT_0] = \psi\{e[(k-i)T_0],\ e[(k-i+1)T_0],\ \ldots,\ e[kT_0], \\ u[(k-j-1)T_0],\ u[(k-j)T_0],\ \ldots,\ u[(k-1)T_0]\}; \\ 0 \leqslant i \leqslant k;\ \ 0 \leqslant j \leqslant k-1;\ \ k = 0, 1, 2, 3, \ldots, \end{gathered} \tag{1.3}$$

where ψ = some function of the arguments on the right side.

If this function is nonlinear, it can be written in the form of a difference equation:

$$\begin{gathered} u[kT_0] = a_n e[(k-n)T_0] + a_{n-1} e[(k-n+1)T_0] + \ldots + a_0 e[kT_0] - \\ - b_m u[(k-m)T_0] - b_{m-1} u[(k-m+1)T_0] - \ldots - b_1 u[(k-1)T_0]. \end{gathered} \tag{1.4}$$

If we use a z-transform [3] on the right and left sides of this equation after having obtained $z = e^{T_0 p}$ (where p = Laplace variable), we obtain the TsUM's z-OPF:

$$D[z] = \frac{u[z]}{e[z]} = \frac{a_n z^{-n} + a_{n-1} z^{-(n-1)} + \ldots + a_1 z^{-1} + a_0}{b_m z^{-m} + b_{m-1} z^{-(m-1)} + \ldots + b_1 z^{-1} + 1}. \tag{1.5}$$

The z-OPF is analogous to the equalizer's OPF for a continuous system, it being the case that $m \leqslant n$. However, the essential difference in this OPF is that it gives only the relationship between the discrete values of the TsUM's input and output signals. In this respect, the expression $z^{-n} = e^{-nT_0 p}$ can be regarded as a lag in the signal's discrete value by n discreteness periods T_0.

The Ts/K converter carries out the reverse conversion of the signal's sequence of digital values at the TsUM's outlet into the drive control signal $\varphi(t)$. The specific form of this signal depends on the type of drive.

The following types of drives are known at the present time: continuous, pulsed, step and digital. For a continuous drive, the sequence of digits at the TsUM's outlet is converted -- with the help of the Ts/K unit -- into a signal that is piecewise-continuous and constant over the discreteness period T_0 (Figure 1.19). If the drive has a sufficiently fast operating speed, it generates an input signal during each discreteness period T_0, as is shown in the figure.

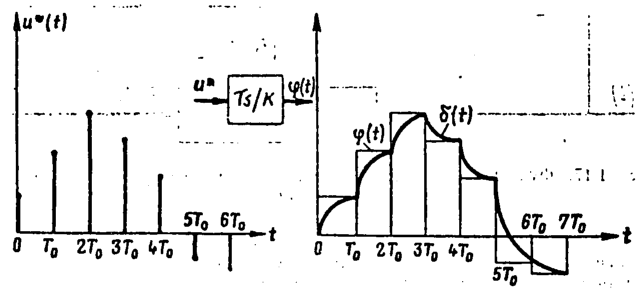


Figure 1.19. Conversion of discrete signal into a piecewise-continuous one.

The nature of the change in the drive's output coordinate has the form of curve $\delta(t)$. The operation of obtaining a constant control signal in the period T_0 is called recall of the signal's discrete value, while the component that performs this operation is the zero-order fixing component. For this component the OPF has the form

$$W_{fc}(p) = \frac{1 - e^{-T_0 p}}{p}. \quad (1.6)$$

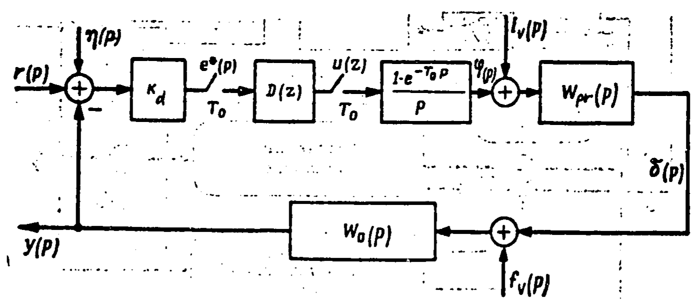


Figure 1.20. Structural diagram of a linear, discrete, single-circuit SAU.

The controlled object and the continuous drive are described by normal differential equations in the same manner as for a continuous SAU. Therefore, the structural diagram of a linear, discrete, single-circuit SAU has the form shown in Figure 1.20. If the discreteness period and the coefficients of the object's, drive's and regulator's OPF's are known, this structural diagram gives exhaustive information for investigating and evaluating the properties of the discrete SAU. If the D[z] coefficients are not given, then for the purpose of determining the TsUM's optimum algorithm for generating the control signal they are found by methods developed in the theory of discrete SAU's.

1.4.3. Multicircuit and Multidimensional Systems

In contrast to single-circuit SAU's, it is irrational to represent complex multicircuit and multidimensional SAU's in the form of a normal structure with an OPF. Let us examine, for example, the functional diagram of a solid-fuel rocket's pitch angle control system that allows for the effect on the system's dynamics of elastic tones from the vibration of the hull [8]. In the object equations we will take into consideration the deviation of the rocket's center of mass in the direction of the normal to the trajectory. In this case the object of control is described by moment and force equations and the equations of the tones from the hull's elastic vibrations. Let us assume that the system has three sensors of generalized output coordinates: a pitch angle sensor, an angular pitch velocity sensor and a sensor of linear velocity along the normal to the trajectory. The functional diagram of such a system is shown in Figure 1.21. The mathematical model of the object contains the following deviation equations:

$$\left.\begin{aligned} &1.\ \Delta\dot{V}_y + C_{VV}\Delta V_y + C_{V\vartheta}\Delta\vartheta + C_{V\delta}\Delta\delta = \frac{F_V}{m};\\ &2.\ \Delta\ddot{\vartheta} + C_{\vartheta V}\Delta V_y + C_{\vartheta\vartheta}\Delta\vartheta + C_{\vartheta\delta}\Delta\delta = \frac{M_\vartheta}{J};\\ &3.\ \Delta\ddot{q}_j + C_{q_j q_j}\Delta\dot{q}_j + C_{q_j q_j}\Delta q_j = C_{q_j\delta}\Delta\delta;\quad j = 1, 2, \ldots, m, \end{aligned}\right\} \qquad (1.7)$$

where ΔV_y = deviation of the rocket's velocity along the normal to the trajectory; $\Delta\vartheta$ = pitch angle deviation; Δq_j = deviation of the axis's angles of inclination for the j-th tone of the rocket hull's elastic vibrations; $\Delta\delta$ = deviation of the control element's angle of rotation with respect to pitch; F_V = disturbing force along the normal to the trajectory; M_ϑ = disturbing moment; C = differential equation coefficients that are temporally variable.

Let it be noted that the components caused by the hull's elastic vibrations are not taken into consideration in the force and moment equations. These vibrations can exert a significant influence on the readings of the pitch angle and pitch angular velocity sensors, so it is necessary to allow for them in these sensors' equations. Let us introduce into the discussion the steering gear's differential equation:

$$\Delta\ddot{\delta} + a_{\dot{\delta}\dot{\delta}}\Delta\dot{\delta} + a_{\delta\delta}\Delta\delta = k_{pr}\Delta u_1, \qquad (1.8)$$

where Δu_1 = the amplifier-converter's control signal.

An analysis of the system of differential equations that takes into consideration a single tone of the flexible vibrations (m = 1) shows that the object (including the drive) can be described by a system of seven first-order differential equations.

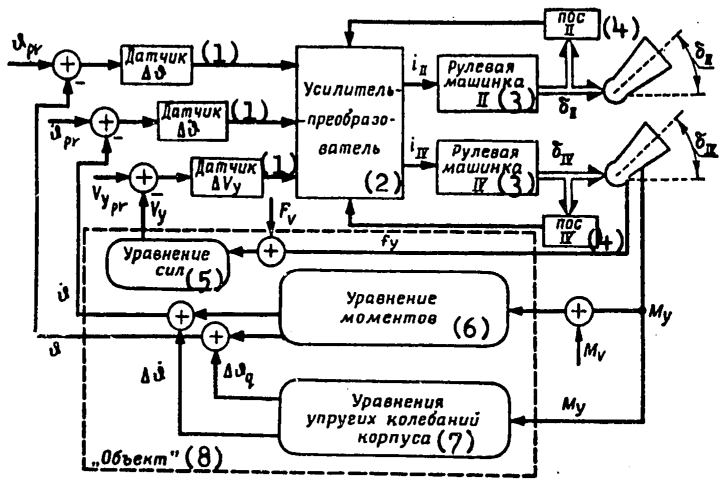


Figure 1.21. Functional diagram of a multicircuit flight control system for a solid-fuel rocket.

Key:

1. Sensor
2. Amplifier-converter
3. Steering actuator
4. POS
5. Force equation
6. Moment equation
7. Equations of the elastic vibrations of the hull
8. "Object"

The system has three sensors and a single independent control action, so it can be placed in the class of unidimensional, multicircuit SAU's. For the mathematic description of this system it is realistic to use vector-matrix equations of the system's spatial states. For this purpose, let us introduce some new designations for the generalized output coordinates and the additional variables (for the hull's elastic vibrations)

$$y_1 = \Delta V_y;\ y_2 = \Delta\vartheta;\ y_3 = \Delta\dot{\vartheta};\ y_4 = \Delta\delta_y;\ y_5 = \Delta\dot{\delta}_y;\ y_6 = \Delta q_1;\ y_7 = \Delta\dot{q}_1.$$

System of equations (1.7) and equation (1.8) can then be reduced to the following form:

$$\left.\begin{aligned} \dot{y}_1 &= b_{11}y_1 + b_{12}y_2 + \ldots + b_{17}y_7 + a_{11}u_1 + c_{11}f_1 + c_{12}f_2; \\ \dot{y}_2 &= b_{21}y_1 + b_{22}y_2 + \ldots + b_{27}y_7 + a_{21}u_1 + c_{21}f_1 + c_{22}f_2; \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \dot{y}_7 &= b_{71}y_1 + b_{72}y_2 + \ldots + b_{77}y_7 + a_{71}u_1 + c_{71}f_1 + c_{72}f_2. \end{aligned}\right\} \quad (1.9)$$

In vector-matrix form this system is written as

$$\dot{Y} = BY + Au_1 + CF, \quad (1.10)$$

where Y = vector of state of the object with dimensionality

$n = 7$; u_1 = control action with dimensionality $\ell = 1$; F = vector of external disturbances with dimensionality $g = 2$; B = = matrix of coefficients of the object, with dimensionality (7 x 7); A = vector of the coefficients affiliated with the control action, with dimensionality $n = 7$; C = matrix of the coefficients affiliated with the disturbances, with dimensionality (7 x 7).

Let us write the system of equations for generating the control action as:

$$\dot{U}_1 = Ku_1 + M'\Delta X, \tag{1.11}$$

where ΔX = vector of the deviations of the output coordinates, with dimensionality $m = 3$, as measured by the sensors; M = vector of the coefficients affiliated with the deviations; K = coefficient affiliated with the control action.

The equation of the system's sensors has the form

$$X = DY + V, \tag{1.12}$$

where D = matrix of the sensor's coefficients, with dimensionality (3 x 7); V = vector of interference at the sensors' outputs, with dimensionality $m = 3$; X = vector of the output coordinates, as measured by the sensors, with dimensionality $m = 3$.

The equation of the deviations of the output coordinates' actual values from the required ones is written as

$$\Delta X = X_{pr} - X, \tag{1.13}$$

where X_{pr} = vector of the output coordinates' programmed values, with dimensionality $m = 3$.

In the general case, for a multicircuit and multidimensional linear SAR it is possible to write vector-matrix equations similar to expressions (1.10)-(1.13), where when $\ell > 1$ we will have, instead of scalar u_1, vector U with dimensionality ℓ and matrices $A_{(n \times \ell)}$, $K_{(\ell \times \ell)}$ and $M_{(\ell \times m)}$.

A structural-matrix diagram of a multicircuit and multidimension SAU constructed in accordance with equations (1.10)-(1.13) is shown in Figure 1.22, where in terms of I_1 and I_2 we define the diagonal matrices with integration operators of the form

$$I = \begin{Vmatrix} \frac{1}{p} & 0 & 0 & \ldots & 0 \\ 0 & \frac{1}{p} & 0 & \ldots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & \ldots & \frac{1}{p} \end{Vmatrix}. \tag{1.14}$$

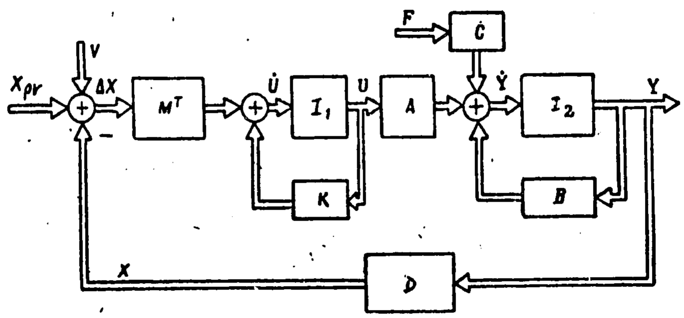


Figure 1.22. Structural-matrix diagram of a continuous multicircuit and multidimensional SAU.

Matrix I_1 has dimensionality (ℓ x ℓ), while for matrix I_2 it is (n x n). The double arrows designate vectors. The structural-matrix diagram in Figure 1.22 fully defines all the properties of a continuous multicircuit and multidimensional SAU if its matrices and initial conditions Y_i and U_i are known. In the case of a system with a TsUM in the control circuit, the structural-matrix diagram undergoes changes. Instead of a system of differential equations of the form

$$\dot{U} = KU + M^{*} \Delta X \tag{1.15}$$

we write the difference vector-matrix equation corresponding to the control signal generation algorithm:

$$U[kT_0] = \sum_{i=0}^{n} B_i \Delta X[(k-i)T_0] - \sum_{i=1}^{m} C_i U[(k-i)T_0], \tag{1.16}$$

where B_i = matrices with coefficients of the control signal generation algorithm, with dimensionality (ℓ x n); C_i = matrices of the feedback coefficients affiliated with the control signals, with dimensionality (ℓ x ℓ).

If we take the z-transform of both parts of equation (1.16), we obtain the z-OPF matrix in the form

$$D[z] = \begin{Vmatrix} d_{11}[z] & d_{12}[z] \ldots d_{1n}[z] \\ d_{21}[z] & d_{22}[z] \ldots d_{2n}[z] \\ \cdots & \cdots \\ d_{l1}[z] & d_{l2}[z] \ldots d_{ln}[z] \end{Vmatrix}, \tag{1.17}$$

where $d_{ij}[z]$ is the z-OPF relationship of the z-representation of the i-th control output signal $u_i[z]$ to the z-representation of the j-th output deviation $\Delta x_j[z]$ in the form

$$d_{ij}[z] = \frac{a_{nj}z^{-n} + a_{n-1j}z^{-(n-1)} + \ldots + a_{0j}}{c_{mj}z^{-m} + c_{m-1j}z^{-(m-1)} + \ldots + 1}. \tag{1.18}$$

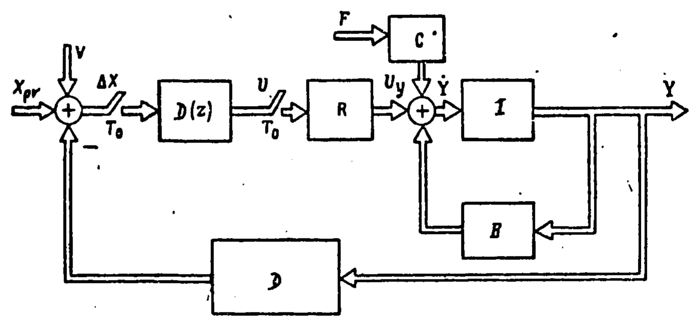


Figure 1.23. Structural-matrix diagram of a discrete multicircuit and multidimensional SAU.

Figure 1.23 is a structural-matrix diagram of such a system, where R designates the diagonal matrix with the OPF of the zero-order fixing components:

$$R=\left\|\begin{matrix}\frac{1-e^{-T_0p}}{p} & 0 & 0\ldots & 0\\ 0 & \frac{1-e^{-T_0p}}{p} & 0\ldots & 0\\ \ldots & \ldots & \ldots & \ldots\\ 0 & 0 & 0\ldots & \frac{1-e^{-T_0p}}{p}\end{matrix}\right\|. \qquad (1.19)$$

It should be kept in mind that all the switches in this layout must be triggered simultaneously, with discreteness period T_0. If this is not done and other discreteness periods $T_{10} \neq T_0$ occur for some channels, the SAU will be multiperiodic. The analysis and synthesis of multiperiodic SAU's poses a considerably more complex problem than for uniperiodic ones.

In succeeding chapters we will first discuss methods of analyzing synthesizing linear continuous and discrete SAU's, and then methods for investigating nonlinear SAU's.

The solution of the analysis and synthesis problem is illustrated by examples from the area of military systems, such as guided missiles, aircraft and radar stations.

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